10/539766
JC17 Rec'd PCT/PTO 20 JUN 2005

VIBRATING RATE GYRO WITH SLAVING OF DETECTION FREQUENCY EXCITATION FREQUENCY

The invention relates to a vibrating gyroscope.

The operating principle of a vibrating gyroscope is explained in relation to figure 1.

A mass M is suspended from a rigid frame C by means of two springs, of stiffness K_x and K_y. It therefore possesses two degrees of freedom, along the x and y directions.

The system may be considered as an assembly of two resonators having eigenfrequencies or natural frequencies F_x along x and F_y along y.

The mass M is excited at its natural frequency F_x along the x axis.

When a speed of rotation Ω about the third, z axis is present, the Coriolis forces induce coupling between the two resonators, causing the mass to vibrate along the y axis.

The amplitude of the movement along y is then proportional to the speed of rotation Ω.

This amplitude is also a function of the difference in the natural frequencies F_x and F_y - maximum sensitivity is achieved when the two natural frequencies are equal.

In particular, for high-performance gyroscopes, it is necessary to obtain maximum sensitivity of the displacement relative to the speed of rotation. It is therefore very desirable to make these frequencies equal.

However, when the frequency equality condition is met, the bandwidth of the gyroscope becomes very small. To increase it, the detection movement along y is feedback controlled, by applying an electrostatic or electromagnetic force along the y axis to the mass, which force counterbalances the force created by the Coriolis coupling. There is no longer any vibration of the mass along y and it is then the feedback force proportional to the speed of rotation Ω that is measured.

It is therefore desirable in vibrating gyroscopes of higher performance for the movement along the y axis to be feedback controlled and for the frequencies F_x and F_y to be made coincident.

However, the dispersion due to the method of production in manufacture does not allow a perfectly zero frequency difference to be obtained. It is therefore necessary to make an adjustment in order for the two frequencies to be equal.

A first method consists in making these frequencies equal by mechanical balancing. This therefore involves modifying the mass or stiffness characteristics of one or other of the resonators by removing material. This method may be used for carrying out a coarse initial adjustment of the frequencies.

Another method consists in carrying out electrical balancing. By means of electrodes, a variable electrostatic (or electromagnetic) stiffness is added to one of the two resonators so as to vary its natural frequency. This method allows a very fine initial adjustment of the frequencies to be made using an electrical voltage applied to the electrodes.

If a gyroscope whose frequencies have been initially adjusted by one of these methods is used, the initial

adjustment of making the mechanical resonant frequencies F_x and F_y coincide cannot be maintained in the long term and under all environmental conditions.

This is because parasitic mechanical effects and the thermoelasticity effects are not strictly identical in both resonators and these effects may result in a frequency differentiation when the environmental, both mechanical and thermal, conditions vary.

One important object of the invention is therefore to propose a vibrating gyroscope that allows the initial adjustment of making the mechanical resonant frequencies F_x and F_y coincident able to be maintained in the long term and under all environmental conditions.

To achieve this object, the invention proposes a gyroscope comprising at least one mass M capable of vibrating along an x axis at a resonant excitation frequency F_x and capable of vibrating along a y axis perpendicular to the x axis, at a resonant detection frequency F_y, under the effect of a Coriolis force generated by a rotation about a z axis perpendicular to the x and y axes, mainly characterized in that it comprises, connected to the mass or masses M, a feedback control loop for controlling the resonant frequency F_y so that F_y is equal or practically equal to F_x throughout the duration of use of the gyroscope.

This feedback control loop thus makes it possible for the stiffness K_y to be permanently feedback-controlled so as to make the natural frequencies F_x and F_y along the two directions equal.

According to one feature of the invention, the gyroscope includes a signal generator for generating a signal that disturbs the vibration of the mass M along y, said generator being connected to the mass M, and

the feedback control loop comprises: means for modifying the resonant detection frequency F_y, means for detecting the variation, induced by the disturbing signal, in the vibration of the mass M along y, an error signal representative of the difference between F_x and F_y being deduced from this variation, and control means for controlling the F_y-modifying means, the control being established on the basis of the error signal.

According to a first embodiment of the invention, the disturbing-signal generator is connected to the mass M via the F_y-modifying means.

According to another embodiment, when the gyroscope includes excitation means for exciting the mass M along y with the aim of counterbalancing the vibration along y generated by the Coriolis force, the disturbing-signal generator is connected to the mass M via these excitation means.

Other features and advantages of the invention will become apparent on reading the following detailed description, given by way of nonlimiting example and with reference to the appended drawings in which:

- figure 1 illustrates schematically the operating principle of a vibrating gyroscope;
- figure 2 shows schematically the necessary main components relating to a single mass of a gyroscope according to the prior art;
- figure 3 shows schematically a curve representative of the variation of the amplitude (in dB) of the detection signal $|U_{det,y}|$, corresponding to the movement of the mass along y, as a function of the frequency in Hz of the excitation signal $U_{ex,y}$ according to the prior art;
- figures 4a) and b) show schematically the curves representative of the control signal (in this case a voltage) for controlling the frequency

modulation (fig. 4a) and of the perturbing signal $U_{ex,y}$ frequency-modulated about the central frequency F_x at the frequency F_0 (fig. 4b), expressed as a function of time;

- figures 5a), 5b) and 5c) show schematically, according to whether $F_y > F_x$, $F_y = F_x$ or $F_y < F_x$, the curves corresponding to those of figures 3 and 4a) and also the corresponding variation of the amplitude of the detection signal $\Delta|U_{det,y}|$;
- figure 6a) shows schematically the detection signal $U_{det,y}$, the envelope of which is given by $\Delta|U_{det,y}|$ for the case in which $F_x \neq F_y$; shown respectively in figures 6b) and 6c) are a reference demodulation signal of frequency F_0 and an error signal e;
- figure 7 shows schematically the necessary main components relating to a signal mass in an example of a gyroscope according to the invention; and
- figure 8 shows schematically the necessary main components relating to a signal mass of another example of a gyroscope according to the invention.

High-precision vibrating gyroscopes generally have two symmetrical vibrating masses operating in what is called tuning-fork mode.

In micromachined sensors, the excitation movement is generally provided by electrostatic forces along the x direction. These forces are often created by means of electrostatic combs.

The detection movement is picked up along a y direction perpendicular to x. In the case of micromachined sensors produced in a plane structure, this y direction may, depending on the case, lie in the plane of the plane structure or perpendicular to this plane.

Figure 2 shows the necessary main components relating to a single mass, for the sake of simplicity.

Conventionally, means are provided:

- for applying excitation forces along the x direction and for detecting the movement of the masses along x so as to feedback control these excitation forces;
- for detecting the movement of the masses along the y direction; and
- for applying feedback forces to the masses along y, these forces being intended to counterbalance the forces created by the Coriolis coupling along y.

These means generally consist of sets of electrodes. The x and y resonators therefore have various types of electrodes:

- excitation electrodes 1, for applying an excitation force along x proportional to a control voltage $U_{ex,x}$, and detection electrodes 2 that deliver a detection voltage $U_{det,x}$ proportional to the movement along x;
- detection electrodes 3 that deliver a detection voltage $U_{det,y}$ proportional to the movement along y; and
- feedback electrodes 4 which are in fact excitation electrodes for applying a feedback force to the y resonator proportional to a control voltage $U_{ex,y}$.

The means 2 for detecting the movement of the mass along x are connected to the means 1 for applying excitation forces along the x direction via an oscillator 5 and an amplitude regulation device 6 placed in parallel with the oscillator 5.

An excitation or feedback loop for excitation along y comprises the following elements. The means 3 for detecting the movement of the mass along y are connected to the means 4 for applying feedback forces along the y direction by a shaping device 7, in series with a synchronous demodulator 8, a corrector 9 and then a modulator 10. The output signal from the gyroscope comes from the corrector 9.

The object of the invention is to provide permanent feedback control of F_y, for example by controlling the stiffness K_y, so as to make the natural frequencies F_y and F_x equal. To do this, a feedback control loop is proposed, which includes F_y-modifying means 11 (shown in figures 7 and 8) such as, for example, electrodes for controlling the stiffness K_y, which are controlled on the basis of an error signal representative of the difference between F_x and F_y. The error signal is determined as follows.

Figure 3 shows schematically a curve representative of the variation of the amplitude (in dB) of the signal $|U_{det,y}|$ coming from the electrodes for detecting the movement of the mass along y, as a function of the frequency in Hz of the excitation signal $U_{ex,y}$ applied to the excitation electrodes. This curve shows a maximum when $F_x = F_y$ and decreases otherwise.

By disturbing the frequency of the excitation signal $U_{ex,y}$, that is to say by applying a disturbing force along O_y to the mass, a disturbance of the detection signal, corresponding to the movement of the mass along y, is obtained, this disturbance being representative of the error signal.

The disturbing force is generated by applying, to the y excitation electrode 4, a disturbing voltage $U_{ex,y}$ frequency-modulated about the central frequency F_x at the frequency F_0 of the following form:

$$U_{ex,y} = U_{ex,0} \sin(2\pi(F_x + \Delta F \sin(2\pi F_0 t) t),$$

$U_{ex,0}$ being a constant.

$U_{ex,y}$ is shown in figure 4b) and obtained by applying, to an oscillator, a signal (in this case a voltage) for controlling the frequency modulation shown in figure 4a).

Figure 4b) indicates certain frequencies of $U_{ex,y}$.

In practice, the frequency modulation is not necessarily sinusoidal, but triangular. F_0 is chosen to be above the bandwidth of the gyroscope, but very much below F_x. For example, ΔF is about 10% of F_x.

Depending on whether the resonant frequency F_y is below, equal to or above the excitation frequency F_x, the variations in the amplitude of the detection signal $|U_{det,y}|$ will be different:

if $F_y > F_x$, $\Delta|U_{det,y}| = u \sin(2\pi F_0 t)$ (sector 1, shown in figure 5a)

if $F_y = F_x$, $\Delta|U_{det,y}| = u \sin(4\pi F_0 t)$ (sector 2, shown in figure 5b)

if $F_y < F_x$, $\Delta|U_{det,y}| = -u \sin(2\pi F_0 t)$ (sector 3, shown in figure 5c).

These variations in the amplitude of the detection signal $|U_{det,y}|$ are thus representative of the difference in F_x and F_y: the error signal e is deduced from this difference.

Depending on the sector in question, the amplitude of the error signal is a signal of frequency F_0 in phase with the control signal (sector 1) or in phase opposition (sector 3) or a signal of frequency $2F_0$ (sector 2).

These three situations are illustrated in figures 5a), 5b) and 5c), respectively. Each case shows the same curve as that in figure 3 and the variation in the signal for controlling the frequency modulation of $U_{ex,y}$ as shown in figure 4a), and the corresponding variation in the amplitude of the detection signal $\Delta|U_{det,y}|$ from which the error signal e is deduced.

In the case of figure 5a) where $F_x < F_y$, $\Delta|U_{det,y}|$ is a signal of frequency F_0 in phase with the control signal.

In the case of figure 5b) where $F_x = F_y$, $\Delta|U_{det,y}|$ is a signal of frequency $2F_0$.

In the case of figure 5c) where $F_x > F_y$ $\Delta|U_{det,y}|$ is a signal of frequency F_0 in phase opposition with the control signal.

Figure 6a) shows the detection signal $U_{det,y}$, the envelope of which is shown as $\Delta|U_{det,y}|$ in the case of which $F_x \neq F_y$. A demodulation reference signal of frequency F_0 and the error signal e coming from the synchronous demodulation device 15 are shown in figures 6b) and 6c) respectively.

A gyroscope according to the invention will now be described. It comprises, as shown in figure 7, in addition to the elements described in relation to figure 2 and identified by the same references, a signal generator 12 for generating a signal that disturbs the vibration of the mass along y, connected to the mass M, and a feedback control loop for slaving the resonant frequency F_y to the frequency F_x.

The disturbing force is generated by applying, to the y excitation electrode 4, by means of the generator 12 such as a VCO (voltage-controlled oscillator) connected to the y excitation loop, a disturbing voltage $U_{ex,y}$ frequency-modulated about the central frequency F_x at the frequency F_0. The control signal from the oscillator is that shown in figure 4a).

The feedback control loop comprises the following elements.

The amplitude of the signal $U_{det,y}$ is recovered by means of an amplitude detector 13 after a shaping device 7 has shaped the signal coming from the detection electrodes 3. This detector 13 delivers $|U_{det,y}|$ and, after the signal $|U_{det,y}|$ has passed through an F_0-centered narrow band-pass filter 14 and then through an F_0 reference frequency demodulator 15, an error signal e is produced, which becomes zero when the frequency F_y becomes equal to F_x.

After integration by means of an integrator/corrector 16, this error signal may control a voltage V on the stiffness electrode 11 that modifies the stiffness K_y and therefore the frequency F_y.

The natural frequency F_y of the mass M along y is therefore properly slaved to the natural frequency F_x along x.

In the case described above, a disturbing force was applied to the mass along y by modulating the frequency of the excitation signal.

Rather than modulating the excitation frequency, it is possible, according to a variant of the invention, to modulate the amplitude of the electrostatic stiffness.

In this case, a voltage $V + v_0\sin(2\pi F_0 t)$ is applied to the stiffness electrode 11. The effect on the detection signal is then equivalent to that obtained by modulating the frequency of the excitation signal.

Figure 8 shows the gyroscope corresponding to this variant. The disturbing force is then generated by applying, to the y stiffness electrode 11, the disturbing voltage $v_0\sin(2\pi F_0 t)$ generated by an oscillator (12') centered on the frequency F_0, connected to the feedback control loop for slaving F_y

to F_x. The feedback control loop is the same as that described in relation to figure 7.

The various elements described in relation to figures 2, 7 and 8 may of course be produced in analogue or digital technology.

The vibrating gyroscope according to the invention may have a plane or three-dimensional structure. It may or may not be micromachined.